

Cryogenic Propulsion Stage (CPS) Configuration in Support of NASA's Multiple Design Reference Missions (DRMs)

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ABSTRACT

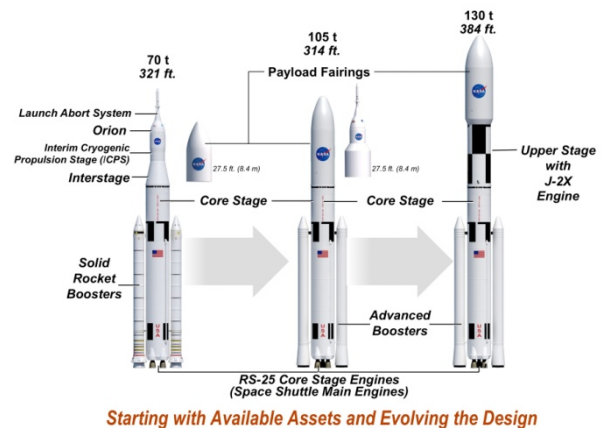
In support of the National Aeronautics and Space Administration's (NASA) Human Exploration and Operations Mission Directorate (HEOMD), the Space Launch System (SLS) is being designed for safe, affordable, and sustainable human and scientific exploration missions beyond Earth's orbit (BEO).

The SLS Team is tasked with developing a system capable of safely and repeatedly lofting a new fleet of spaceflight vehicles beyond Earth orbit. The Cryogenic Propulsion Stage (CPS) is a key enabler for evolving the SLS capability for BEO missions. This paper reports on the methodology and initial recommendations relative to the CPS, giving a brief retrospective of early studies on this promising propulsion hardware. This paper provides an overview of the requirements development and CPS configuration in support of NASA's multiple Design Reference Missions (DRMs).

BACKGROUND

The SLS initial configuration comprises a 27.5-foot (8.4-meter)-diameter core stage powered by four liquid oxygen/liquid hydrogen (LOX/LH₂) RS-25 core stage engines (space shuttle main engines) presently in NASA's inventory, combined with five-segment solid rocket boosters (SRBs) currently in the testing phase, to lift 70 metric tons (t) of payload to low-Earth orbit (LEO), Figure 1. This is the basic Block 1 configuration for the first two BEO flights of the Orion Multi-Purpose Crew Vehicle (MPCV). By way of comparison, the SLS

Block 1 has 10 percent more thrust than the Saturn V.



**Figure 1. SLS Block 1 (70 t), Block 1A (105 t),
and Block 2 (130 t).**

The SLS development strategy also includes a series of on-ramps for affordably increasing both the capacity and sustainability of this unique national asset. Through a series of planned block upgrades, the SLS will be evolved to a 105-t (Block 1A) and a 130-t (Block 2) capability, which has 20 percent more thrust than the Saturn V. This plan delivers an initial capability within near-term schedule and budget targets, as well as engages the U.S. aerospace workforce and infrastructure, while providing a flexible platform for reaching new destinations in the solar system and performing entirely new missions.

The first Orion BEO mission in 2017 will be an autonomous flight of the full-up spacecraft around the Moon to verify its performance for crewed flight in 2021; on a longer-duration circumlunar

mission to further verify system integrity. With these as anchor flights, NASA is investigating other potential payloads and missions, both internally and with domestic and international partners.

INTRODUCTION

The CPS is an in-space cryogenic propulsive stage based largely on state-of-the-practice design for launch vehicle upper stages. However, unlike conventional propulsive stages, it also contains power generation, avionics, and reaction control and thermal control systems to limit the loss of liquid hydrogen and oxygen due to boil-off during extended in-space storage, while providing the capability for in-space loiter, engine restart, and automated rendezvous and docking (AR&D).

The CPS provides the necessary change in velocity (ΔV) for rapid transfer of in-space elements to their destinations or staging points as part of the capability-driven exploration framework, figure 2. The CPS allows expansion to multiple missions and destinations such as Near Earth Asteroids (NEA), Mars, and Earth-Moon L1/L2 Lagrange points.



Figure 2. NASA's Capability-Driven Exploration Framework.

The CPS is designed using a block upgrade strategy to provide maximum mission/architecture flexibility. CPS is designed to meet DRMs provided by the NASA Human Spaceflight Architecture Team (HAT). Derived requirements are given in Table 1.



Figure 3. The Cryogenic Propulsion Stage (CPS).

The Block 1 CPS is designed to meet short duration flight times (hours) requirements with passive cryo fluid management. Requirements for the Block 2 CPS (as shown in Figure 3) are for long duration flight times (days/weeks/months) with active and passive cryo fluid management.

Table 1. CPS Derived Requirements.

Main Engine	Total Thrust: 60,000 pounds of force (lbf) Specific impulse (I_{sp}): 465 seconds Restarts: Up to 5
Total Mass	100 t or less
LEO Loiter Time	6 hr to 1 year
Circularize Capability	Responsible for circularizing itself and payloads from the SLS insertion orbit (-87 x 241 kilometers (km)) to a LEO orbit (407 x 407 km)
Attitude Control	Provides attitude control for itself and payloads during mission event where CPS is actively thrusting
Automated Rendezvous and Docking (AR&D)	Provides maneuver propellants and equipment for AR&D, both active & passive

DESIGN OVERVIEW

Although performance requirements and architecture are factors in CPS design and configuration, meeting affordability, safety, and sustainability goals provides the basis of the design solutions. DRMs utilized in the study are from the HAT Cycle C. The DRM scenarios investigated were not prioritized but were used for understanding the capability required. NASA continues to work with its international partners on multiple mission scenarios.

Commonality was a major driver in the defining the configurations point of departure. Critical sub-elements that drove affordability, sustainability, and safety were deemed critical. The team ensured that the block 1 and block 2 CPS designs shared critical sub-elements, including main propulsion tanks, main engine, primary structure, reaction control system, and avionics. A review of the concept of operations and functionality is presented prior to reviewing the CPS detailed configuration.

CONCEPT OF OPERATIONS

The Mission Timeline and Concept of Operations (CONOPS) were used to define the desired operational system characteristics and concepts to provide the necessary understanding of integration issues needed in the development of the design requirements for the CPS. This analysis was primarily targeted at defining the performance goals of the CPS.

Summaries of the Earth-Moon Lagrange 2 (EM-L2), Near Earth Asteroid (NEA), Lunar Surface Polar Access missions are provided below to aid the reader in their understanding of the needed functionality of the CPS (Figure 4).

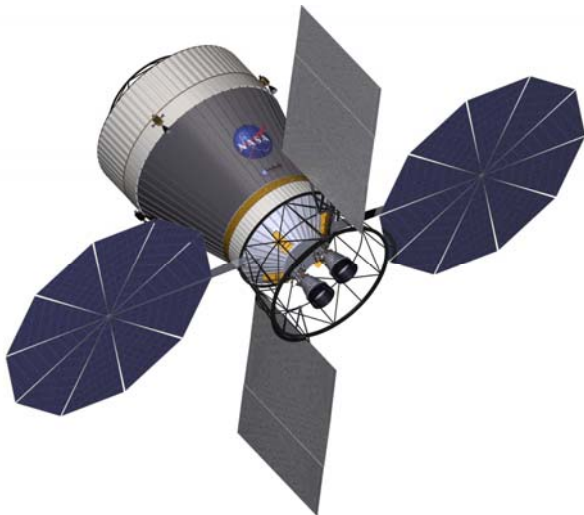


Figure 4. The CPS Block 2 Configuration in mission mode.

Earth-Moon Lagrange 2 Mission (EM-L2)

The Earth-Moon Lagrange 2 (EM-L2) flight is a mission to transport crew to the EM-L2 for exploration, and scientific study. A secondary objective of the mission is to study the effects of deep space missions on the crew and equipment.

The EM-L2 Mission CONOPS consists of several phases that include (1) Low Earth Orbit (LEO) injection and loiter; (2) Earth departure toward the Moon; (3) transit to the Moon; (4) lunar swing-by maneuver; (5) transit to EM-L2; (6) EM-L2 arrival; and (7) return to Earth. A pictorial view of the EM-L2 mission is shown in Figure 5.

LEO Injection and Loiter: The launch vehicle consists of the SLS and CPS. The SLS provides insertion of the Orion Multi Purpose Crew Module (MPCV) into a highly elliptical orbit such as -86.9 km x 240.8 km. The CPS and Orion capsule are separated from the SLS and proceed to a circular LEO of 240.8 km by 240.8 km. The CPS and Orion capsule remain in orbit for solar array deployment and checkout. During this time, it is assumed that the CPS will provide LEO attitude control for itself and Orion until arrival at EM-L2.

Earth Departure: Once checkout and deployment are complete, the CPS performs the Earth departure burn with its main engines to start the transit of CPS and Orion capsule toward the Moon.

Transit to the Moon: After the Earth departure burn is complete, the CPS remains docked to MPCV and continues to provide attitude control and Thrust Correction Maneuvers (TCM) for the stack for the multi day transit.

Lunar Swing-By: Once at the Moon, the CPS provides a main engine burn with the assistance of lunar gravity to continue on its path to EM-L2.

Transit to EM-L2: After the lunar swing-by maneuver is complete, the CPS/MPCV begins the three-day transit to EM-L2. The CPS continues to provide attitude control and TCMs.

EM-L2 Arrival: Upon arrival at EM-L2, CPS provides the arrival burn via its main engines to insert the MPCV into a halo orbit around L2. After verification of the proper orbit, the CPS separates from Orion and performs a final disposal burn. Re-

quirements for the disposal are notional at this point.

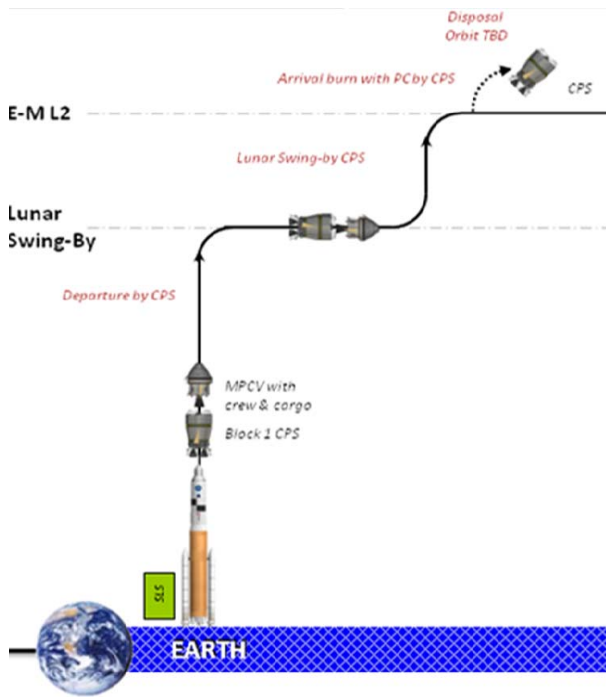


Figure 5: Earth-Moon Lagrange Point 2 Design Reference Mission.

Near Earth Asteroid (NEA) Mission

The Near Earth Asteroid (NEA) mission is a mission to transport crew to the NEA for human exploration and scientific study. A secondary objective of the mission is to study the effects of deep space missions on the crew and equipment. It should be noted NEA missions may require two SLS launches to mitigate mission duration supply impacts due to deep space mission environments and transit time.

The NEA Mission CONOPS consists of several phases that include (1) Low Earth Orbit (LEO) injection and loiter; (2) Earth departure toward the Moon; (3) transit to the Moon; (4) lunar swing-by maneuver; (5) transit to EM-NEA; (6) EM-NEA arrival; and (7) return to Earth.

LEO Injection and Loiter: The launch vehicle consists of the SLS and CPS. The SLS provides insertion of the Orion MPCV into a highly elliptical orbit such as -86.9 km x 240.8 km. The CPS and Orion capsule are separated from the SLS and proceed to a circular LEO of 240.8 km by 240.8 km. The CPS and Orion capsule remain in orbit for solar array deployment and checkout. During this time, it is assumed that the CPS will provide LEO

attitude control for itself and Orion until arrival at EM-NEA.

Earth Departure: Once checkout and deployment are complete, the CPS performs the Earth departure burn with its main engines to start the transit of CPS and Orion capsule toward the Moon.

Transit to the Moon: After the Earth departure burn is complete, the CPS remains docked to MPCV and continues to provide attitude control and TCM for the stack for the multi day transit.

Lunar Swing-By: Once at the Moon, the CPS provides a main engine burn with the assistance of lunar gravity to continue on its path to EM-NEA.

Transit to EM-NEA: After the lunar swing-by maneuver is complete, the CPS/MPCV begins the three-day transit to EM-NEA. The CPS continues to provide attitude control and TCMs.

EM-NEA Arrival: Upon arrival at EM-NEA, CPS provides the arrival burn via its main engines to insert the MPCV into a orbit path with the NEA. After verification of the proper orbit path, the CPS separates from Orion and performs a final disposal burn. Requirements for the disposal are notional at this point.

Lunar Surface Polar Access Mission

The Lunar Surface Polar Access mission is a mission to transport crew to the Moon's surface for human lunar exploration and scientific study. The lunar surface mission requires the use of two SLS launch vehicles to perform the mission. The first launch carries a lunar lander from Earth to a circular orbit about the Moon. The second launch delivers the MPCV Orion capsule to the same circular orbit as the lander. Once the Orion capsule and lander arrive in the same orbit, the two elements will rendezvous and dock and complete the mission.

A Lunar Surface Polar Access mission CONOPS consists of several phases that include (1) LEO insertion and loiter; (2) Earth departure toward the Moon; (3) transit to the Moon; (4) lunar arrival; (5) Lunar Orbit Rendezvous (LOR) of the MPCV and lander; (6) lunar landing and ascent, and (7) crew return to earth.

LEO Insertion and Loiter (Launch 1): The first launch consists of the SLS, CPS and lunar lander

element. The SLS provides insertion of the CPS and lander into a highly elliptical orbit of -86.9 km x 240.8 km. During transit to this orbit, the SLS payload fairing is jettisoned. After jettison, the CPS and lander separate from the SLS and proceed to a circular LEO orbit of 240.8 km by 240.8 km. The CPS and lander remain in orbit for hours for lander checkout. CPS is assumed to provide LEO attitude control for itself and lander until lunar arrival.

Earth Departure: Once checkout and deployment are complete, the CPS performs the Earth departure burn, with its main engines, to start the transit of CPS and lander toward the Moon.

Transit to the Moon: After the Earth departure burn is complete, the CPS remains docked to the Lander and continues to provide attitude control and Thrust Correction Maneuvers (TCM) for the stack for the multi day transit.

Lunar Arrival: Once at the Moon, the CPS provides a burn to insert the lander into a 100 km x 100 km circular orbit around the Moon. After verification of the proper orbit, the CPS separates from the lander and performs a final disposal burn.

LEO Injection and Loiter (Launch 2): The second launch consists of the SLS, CPS, and Orion capsule, months after the first launch. The mission operations and performance characteristics of the second launch are identical to the first launch.

Lunar Operations: Once the two payloads are in lunar orbit, the Orion capsule and lander will rendezvous and dock, and perform lunar landing, surface exploration, lunar ascent, and crew return to Earth. Details of the exploration operations are contained in other HAT documentation.

FUNCTIONAL ALLOCATIONS

The purpose of functional analysis and allocation is to produce a coherent description of system functions. This is accomplished by arranging functions in logical sequences, decomposing higher-level functions into lower-level functions, and allocating performance from higher- to lower-level functions. Many of the functional allocations listed in this portion are from CPS work performed for HAT. The CPS team is using functional analysis and allocation to clarify the actions the system will be expected to perform.

Functions are discrete actions (action verbs) necessary to achieve the system's objectives. These functions may be stated explicitly, and are derived from the implied or stated requirements from the DRMs.

Functional and performance requirements at any level in the system are developed from higher-level requirements. Functional Analysis and Allocation is repeated to define successively lower-level functional and performance requirements, thus defining architectures at ever-increasing levels of detail. System requirements are allocated and defined in sufficient detail to provide design and verification criteria to support the integrated system design. This top-down process of translating system level requirements into detailed functional and performance design criteria includes several steps.

First, the system must be defined in functional terms, then decomposed into top-level functions into sub-functions. That is, actions are identified at successively lower levels for what the system has to do.

DRM key functional requirements are translated into detailed functional and performance criteria or constraints.

Next, all internal and external functional interfaces are identified and defined. Functional groupings are identified to minimize and control interfaces (functional partitioning). Functional characteristics of existing or directed components in the system are determined and incorporated into the analysis and allocation.

The life-cycle functions for the elements are examined as appropriate. This includes revisiting the functional analysis and requirements analysis step as necessary to resolve functional issues.

Functional partitioning is the process of grouping functions that fit logically with the components likely to be used, and to minimize functional interfaces. Partitioning is performed as part of functional decomposition. It identifies logical groupings of functions that facilitate the use of modular components and open-system designs.

Since this is an early analysis effort, the functional analysis is presented from a CPS perspective. Therefore, it does not attempt to present a comprehensive analysis of the total launch vehicle and

mission environment under HEOMD such as the Orion capsule or Lander.

The primary focus of the functional analysis was to identify areas that were considered to be key driving factors in the CPS design. Therefore, the functional analysis was targeted from the time of ascent from the launch pad. An on-pad function was included, but sub-functions for this function are not presented in this paper.

Sustainment Functions: Sustainment functions are those functions that the CPS performs regardless of operational activity. The functions include vehicle management, power, MMOD protection, propulsion, hazardous gas control, thermal management, and guidance, navigation and control (GN&C). The CPS will be expected to perform sustainment functions during the EM-L2 and lunar surface missions.

Mission Performance Goals: The mission performance goals for the CPS were determined by assessing various cis-lunar missions. The strategy was to determine the bounds of CPS performance. The functional phases are broken up by the total missions operational function such as on pad, launch, separation, circularization, loiter, deployment, transit, operation, transit and disposal.

The EM-L2 mission provides a minimal ΔV performance goal for cis-lunar space. The Lunar Surface Polar Access mission provides the upper bound goal for cis-lunar space.

CPS CONFIGURATION SUMMARY

The stage characteristic size is approximately seven and half meters in diameter to allow for packaging for all SLS configurations. The CPS length is approximately thirteen meters to allow for packaging within the shroud and to allow for payload packaging constraints. The CPS includes the complete forward structural assembly and payload adapter for integration of the payload. The combined size allows for sizing of payloads up to 40 t on the launch date.

A notional solar array that produces ~22 kilowatts (kW) was found to be functionally appropriate. The power system on the Block 1 CPS utilizes lithium ion batteries for technology readiness and to meet functional requirements. However, the Block 2 is envisioned to utilize UltraFlex Arrays with secondary batteries for redundancy.

The CPS is a LOX/LH₂ system with a 66,900kg propellant capacity. The main propulsion system utilizes two engines from the Air Force Affordable Upper-stage Engine Program (AUSEP). The resulting total thrust is 60,000 lbf with a thrust structure sized for 100,000 lbf.

The reaction control system (RCS) system is baselined to use monomethyl hydrazine (MMH)/nitrogen tetroxide (NTO) propellants; however, opportunities exist to upgrade to other high non-toxic propellant combinations. The RCS system provides lateral and axial thrusters for attitude control and disposal.

Long-term mission survivability is a risk for all CPS sub-elements. The most severe driving CPS duration can be as high as 530 days. The most sensitive system for survivability and mission success is the thermal system. The Block 1 CPS spray-on foam insulation/multi-layer insulation (SOFI/MLI) is a passive system. The Block 2 CPS is envisioned to use a broad area cooler active system including the Block 1 Passive System. The Office of Chief Technologist (OCT) CPST lead program office will be developing and test flying these technologies.

Stage and Propulsion Implications: The CPS has a functionality requiring up to five (5) engine starts for orbit insertion and transfer In-space (e.g. Centaur) lending to expander cycle engines. The high I_{sp} reduces propellant mass and burnout mass. The cycles allow for repeatable discreet transients due to simplicity and inherent power limits of the cycle including wider inlet conditions and boost phase vibration stability.

In addition, with the flexible architecture short burn times for small maneuvers are required to limit ΔV errors. The reduction in the thrust variability leads to lower residuals and thrust dispersions. The low accelerations reduce integrated stack loads for other architecture elements. High stack accelerations are a major issue for HAT DRM elements, which may require deep throttling for burns w/solar arrays deployed.

CONCLUSION AND TECHNICAL STATUS

This initial study suggests that development of a CPS ultimately accelerates the Agency's ability to undertake a full spectrum of DRMs, thus achieving a greater range of mission capture to deliver maximum value for the SLS investment. Overall, CPS on SLS enables exploration missions and provides

a starting point on the path to delivering more capability and capacity for high-priority missions, both domestic and international.

The SLS CPS team continues efforts to meet HAT mission goals and objectives via the Requirements Analysis Cycle (RAC) cycle process. The continued refinement of the stage design and related sensitivities to drive out top-level requirements is critical to ensure affordable, safe, and sustainable exploration. The trade studies conducted in a RAC includes the investigation of long duration cryogenic fluid management for reduced to zero boil-off to propulsion and power assessments.

CPS provides competitive opportunities for industry and academia, as well as provides an opportunity to expand SLS partnerships. SLS combined with CPS evolves the rocket as a new

national capability delivered on time and within budget.

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